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GRB Afterglow Polarimetry Past, Present and Future

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Abstract

Gamma-ray bursts and their afterglows are thought to be produced by an ultrarelativistic jet. One of the most important open questions is the outflow composition: the energy may be carried out from the central source either as kinetic energy (of baryons and/or pairs), or in electromagnetic form (Poynting flux). While the total observable flux may be indistinguishable in both cases, its polarization properties are expected to differ markedly. The later time evolution of afterglow polarization is also a powerful diagnostic of the jet geometry. Again, with subtle and hardly detectable differences in the output flux, we have distinct polarization predictions.

1.1 Introduction

Polarimetry is a powerful diagnostic tool to study spatially unresolved sources at cosmological distances, such as gamma-ray burst (GRB) afterglows. Radiation mechanisms that produce similar spectra can be disentangled by means of their polarization signatures. Also, polarization provides unique insights into the geometry of the source, which remains hidden in the integrated light.

Historically, essentially all interpretative studies about GRB afterglow polarimetry have been based on the cosmological fireball model (26; 33), which we will also use as a reference for our discussion. Afterglow polarization studies have indeed the advantage that different models are often almost indistinguishable in term of radiation output in the optical, but produce markedly distinct predictions about polarization.

In this proceeding, we will briefly review what we have derived by optical afterglow polarimetric observations in Sect. 1.2 and discuss the most recent development in the field in Sect. 1.3. For a deeper discussion about the

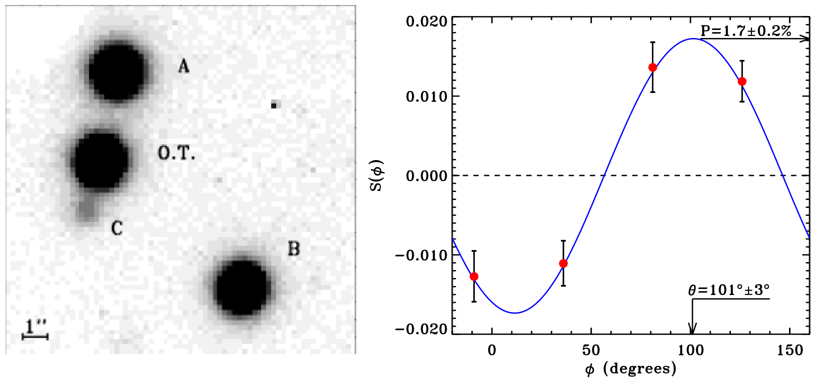

Fig. 1.1. The field of GRB 990510 observed by the ESO-VLT equipped with FORS1 in the R band (left). The net polarization of GRB 990510 (right). From (2).

physical ingredients generating a polarized flux in GRB afterglow radiation one can refer to other proceedings in this volume (15; 17; 6).

1.2 What have we learnt so far?

We report below what we consider the three most important achievements obtained by afterglow polarimetric observation in GRB research. Generally speaking, two general families of models have been developed to explain why GRB afterglows can be polarized and the time evolution of polarization. One possibility is that the emission originates in causally disconnected regions of highly ordered magnetic field, each producing polarization almost at the maximum degree. (13) predicted a $\sim 10\%$ polarization. If the regions have a statistical distribution of energies, the position angle can be different at various wavelengths. This value is greater than that observed in many GRB afterglows (4) as most of the positive detections so far derived are below $\sim 3\%$. In an alternative scenario first introduced by (**?**) and then developed by (10**?**) the magnetic field is ordered in the plane of the shock. In a spherical fireball, such a field configuration would give null polarization, but if a collimated fireball is observed off-axis (as it is most probable), a small degree of polarization would be predicted, with a well defined temporal evolution. Here the ultrarelativistic motion toward the observer and the physical beaming of the outflow are fundamental ingredients.

1.2.1 GRB afterglows polarization

After a few unfruitful attempts which (14), and not by chance as soon as the first unit of the ESO-VLT become operational, a low although highly significant polarization for the afterglow of GRB 990510 (Fig. 1.1) was successfully detected for the first time (2; 31). This simple observational finding carried already a lot of information. First of all, the detection of polarized flux from a GRB afterglow can and has been considered a clear signature for synchrotron emission, although various alternative explanations indeed exist. In general, the detected polarization ($1.7\% \pm 0.2\%$) would require emission processes involving particle acceleration. In the external shock phenomenon we have particle acceleration at the shock front and once we consider the ultrarelativistic motion toward the observer and the physical beaming of the outflow some level of polarization in the afterglows is naturally predicted. It is possible to have some degree of polarization adopting other scenarios, however in no case a polarized flux is a natural output of the model, as it is for the cosmological fireball model. To my knowledge, this is still one of the most convincing, although admittedly often unrecorded, observational proof supporting the standard afterglow model.

1.2.2 Afterglow polarization variable in time

The detection of varying polarization on time scales comparable to those of the afterglow evolution, immediately implies that the observed polarization is intrinsic to the source and not, for instance, due to scattering against material along the line of sight. The first convincing evidence of time-varying polarization was obtained for GRB 020813 (1; 19), where a decrease of the polarization degree from $\sim 3\%$ down to less than 1% (Fig. 1.2), with constant position angle, was recorded from a few hours to half a day after the burst. Evolution was also singled out in GRB 021004 (18).

The most striking example is however GRB 030329. Due to its relatively small distance, a very high quality dataset was obtained covering more than two weeks (12). Strong, somewhat erratic, variations of the polarization degree and position angle during the afterglow evolution were singled out. Polarization variations occurred on a time scale comparable to that of the afterglow flux variability, offering a direct link between the two phenomena (11) although in the case of GRB 030329 the late-time rise of the supernova (associated to the GRB) component played an important role.

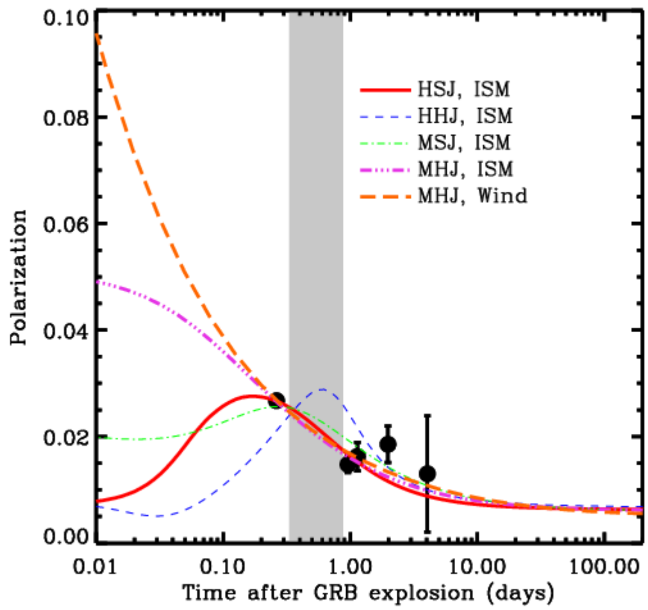

Fig. 1.2. Polarimetric curve of GRB 080213. The observations are compared to predictions for several families of models as discussed in (19). The shaded area shows where a break, possibly a jet break, was observed during the optical afterglow evolution (3).

1.2.3 Afterglow polarization and the geometry of GRB jets

Since GRB sources are unresolved, any model for producing polarization requires some kind of anisotropy in the emitting fluid. The simplest configuration envisages emission from homogenous jets observed off-axis. In this case, as shown by (10; 28), the polarization time evolution presents two maxima, reaching a zero level in between, where a flip of the polarization angle by 90° also occurs. A clear prediction in principle easy to test with observations. More complex jet structures have also been proposed, i.e. in which the energy content per solid angle is decreasing towards the wings of the jet. Such configurations may allow for a unified view of GRBs, in which differences among events arise only (or mostly) from the orientation of the observer with respect to the jet core. The polarization behaviour is in this case markedly different, with a single broad maximum (27; 19).

Up to now, a full set of (late time) observations of polarization evolution could effectively be compared with models only in the case of GRB 020813. The main result of accurate modeling (19) is that homogeneous jet model predictions with shock generated magnetic fields are in clear disagreement

with the observations. This is one of the strongest direct observational evidences against the homogeneous jet scenario so far obtained (see also the case of GRB 030328, (22)).

1.3 *Swift* and the early afterglow

Time-resolved polarimetric observations of late-time (later than about 1 hour) afterglow are extremely demanding, even for 8 m class telescopes, due to the low polarization detected and the rapid fading of the afteeglows. Moreover, the complexity of afterglow behaviors compared to the theoretical predictions made difficult to apply further observational tests and derive unambiguous answers.

However, after the launch of the *Swift* satellite (9), early afterglow observations become feasible thanks also to the network of ground-based robotic telescopes devoted to GRB follow-up. Early afterglow observations can provide powerful diagnostics for many physical ingredients of GRB models, and again polarimetry can help to solve one of the hottest issues of GRB research.

Within the cosmological fireball model a hot fireball (26) expands driven by internal energy. An alternative scenario which attracted great theoretical interest has also been developed (30; 29; 21; 20; 32), the "electromagnetic outflow", where most of the energy is carried to large distances from the central source in electromagnetic form (Poynting flux). Although dramatically different physics are involved, these two scenarios may result in a similar radiation output.

Things are different if polarization is considered. In the early phases optical emission can be generated by the forward shock, i.e. the afterglow, or by the reverse shock responsible for the optical flash. (11) showed that the optical flash, if due to the reverse shock, shares the same magnetic field configuration as the prompt emission, and therefore the same level of linear polarization. If the fireball is electromagnetically dominated, the first tens of minutes of the afterglow may be >40% polarized (16). Optical flash polarization properties probe the magnetic field structure within the original outflow, while the afterglow emission probes the magnetic field structure in the shocked external medium, as well as the jet angular structure. Producing strong polarization in the optical flash requires a large scale ordered magnetic field possibly advected from the inner engine, while if the magnetic field is shock generated, no polarization is expected.

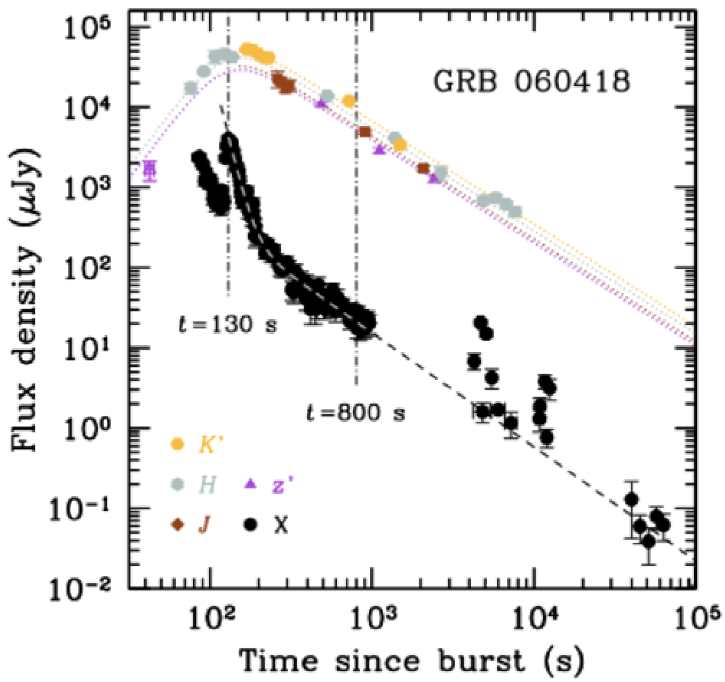

Fig. 1.3. Early afterglow near-infrared and X-ray light curves obtained by the REM telescope and by *Swift* (24). The Liverpool telescope polarimetric measurement (25) was carried out about three minutes after the high-energy event, just after the peak of the near-infrared light curve which was interpreted as the afterglow onset.

1.3.1 Early afterglow observations

To date, the only early polarimetric measurement was performed by (25) deriving an 8% upper limit just after the onset of the afterglow of GRB 060418 (Fig. 1.3). This result could strongly limit the possible role of magnetic fields in driving the outflow dynamics. However, in this case the optical emission is likely due to the forward shock only (24; 8), and the predicted polarization level depends on still poorly known details of the transfer of magnetic energy from the outflow to the shocked circumburst medium (11; 32; 7; 5), so that low or null polarization is still compatible with the theoretical expectations and these measurements are not conclusive yet.

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